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Thrust Augmentation Options for the Beta II Two-Stage-to-Orbit Vehicle

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ABSTRACT

NASA Lewis Research Center is continuing to study propulsion concepts for a horizontal takeoff and landing, fully reusable, two-stage-to-orbit vehicle. This will be capable of launching and returning a 10,000 pound payload to a 100 nautical mile polar orbit using low-risk technology. The vehicle, Beta II, is a derivative of the USAF/Boeing Beta vehicle which was designed to deliver a 50,000 pound payload to a similar orbit. Beta II stages at Mach 6.5 and about 100,000 feet altitude. The propulsion system for the booster is an over/under turbine bypass engine/ramjet configuration. In this paper, several options for thrust augmentation were studied in order to improve the performance of this engine where there was a critical need. Options studies were turbine engine overspeed in the transonic region, water injection at various turbine engine locations also during the transonic region, and water injection at the turbine engine face during high speed operation. The methodology, constraints, propulsion performance and mission study results are presented.

INTRODUCTION

This paper is part of NASA Lewis Research Center's (LeRC) on-going study of propulsion systems for low-risk replacements for the Space Shuttle. NASA LeRC has been addressing critical design areas in order to improve the Beta II booster performance. The purpose of this present study was to predict the improved vehicle performance due to the enhancements made to the booster propulsion system.

The vehicle used for this study, Beta II, is a two-stage-to-orbit (TSTO) vehicle derived from the USAF/Boeing Beta vehicle (ref. 1 & 2). Beta II, a horizontal takeoff and landing vehicle, was downsized from the original Beta to deliver 10,000 pounds to a 100 nautical mile polar orbit. The vehicle configuration is shown in Figure 1.

Beta II was designed to be fully reusable, using low-risk and near-term technology. The total takeoff weight of Beta II (booster and orbiter) was 1 million pounds (ref. 3). The Beta II configuration studied in this paper had four High-Speed Civil Transport (HSCT) derived turbine bypass engines on top and one conventional ramjet at the bottom per nacelle (see Figure 2). A standard hydrocarbon jet fuel was used in both main and afterburner of the HSCT engines and they operated from takeoff to Mach 3 or 3.5. The ramjet used hydrogen fuel and became operational around Mach 1.0 until separation occurred. Also included in this configuration was a variable-capture area inlet for better inlet/engine airflow matching throughout the flight path.

The Beta II booster propulsion system is fully airbreathing from takeoff to separation at Mach 6.5 and 100,000 feet altitude. After separation the booster returns to its landing site. The orbiter, similar to the Space Shuttle orbiter in appearance, is bottom-loaded within the booster to improve mating and staging operations. The orbiter was propelled by one Space Shuttle Main Engine. The orbiter propulsion system operated from booster/orbiter separation to orbit.

Options looked at in this study included turbine engine aerodynamic overspeed and water injection to improve its capability and performance. Mission analysis was then performed to determine the optimum configuration based on the minimum propellant used. Description of the engines and, its constraints, analysis methods, turbine engine performance using various options for thrust enhancement and the accompanying effects on the vehicle will be discussed.

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TURBINE BYPASS ENGINE

The turbine bypass engine (TBE) is used in this study and is illustrated in Figure 3. The TBE is a single-spool, turbojet-like engine that should be optimum for an acceleration mission. The unique feature of the TBE is that it has a bypass valve to bypass some airflow around the main burner and turbine for better compressor-turbine airflow matching. This bypass air is then mixed with the turbine exit flow. This allows higher sea level burner temperatures, while maintaining acceptable compressor surge margins. At sea level static conditions, engine overall pressure ratio was 20.4 and the turbine bypass ratio (ratio of bypass airflow to main airflow) was 0.18 at maximum burner temperatures. From a previous study (ref. 3), the engine corrected airflow was set to 610 pounds per second. Maximum burner temperature was limited to 3560 °R and the engine was operated to limit maximum compressor exit temperature to 1810 °R.

Since this is an acceleration vehicle, maximum afterburning was used to maximize thrust, except for the 5 percent of airflow used for afterburner liner cooling. The TBE and ramjet airflow are supplied by a common inlet. During TBE operation, turbine engine airflow is maximized, within its temperature and mechanical speed constraints, to maximize thrust. The inlet airflow not used by the TBEs is used for the ramjet. The inlet and nozzle performance data came from previous Beta II studies and will not be reported here.

RAMJET

The ramjet size was also determined in a previous study (ref. 4), which set Mach number and altitude limits for the Beta II vehicle. A maximum burner cross-sectional area of 111.3 square feet was used, with a constant cross-sectional area. Nozzle throat area was variable to maximize performance. The ramjet was hydrogen fueled; the fuel-to-air ratio was set to maximize thrust. However, the fuel-to-air ratio was limited to the stoichiometric value, and 5 percent of the ramjet airflow was not burned, but used for cooling.

METHOD OF ANALYSIS

Several codes were used in performing this study. The NASA Engine Performance Program (NEPP) (ref. 5), was used to carry out the turbine engine performance analysis. NEPP performs a one-dimensional, steady-state thermodynamics analysis and includes chemical - equilibrium effects. Compressor and turbine performance maps were used to model the thermodynamic and aerodynamic performance of these components. They were assumed to be similar in technology and performance to those being used in current High Speed Research Studies.

The ramjet performance was calculated using RAMSCRAM (ref. 6). RAMSCRAM is a one-dimensional, steady-state code which includes chemical equilibrium effects for a ramjet or scramjet duct. The user sets loss factors for various portions of the cycle, such as internal performance factors for the inlet, diffuser or nozzle. The program will automatically determine the loss in momentum due to the heat release in the combustor.

The performance data used for the nozzle was from previous Beta II studies using SEAGULL (ref. 7). SEAGULL is a steady-state, inviscid, two-dimensional performance code which uses finite differences method. Nozzle performance included friction, divergence and over or under expansion losses. The inlet performance data was obtained using the Inlet Performance Analysis Code (IPAC) (ref. 8). IPAC makes use of the oblique shock and Prandtl-Meyer expansion theory for the prediction of inlet performance and includes additive, bleed, and spillage drags. Since the performance data generated for the TBE and ramjet was uninstalled data, the INSTALL code (ref. 9) was used to take into account the installation effects of the propulsion system. The INSTALL code was designed to calculate net installed propulsion performance at various flight conditions based on uninstalled engine, inlet and nozzle data.

The mission analysis was performed using the Optimal Trajectories by Implicit Simulation program (OTIS) (ref. 10). OTIS simulates and optimizes point mass trajectories with provisions made for free and fixed end constraints, specified way points and path constraints. OTIS was used to find optimal trajectories to maximize weight at staging (minimize propellant usage), while satisfying maximum dynamic pressure, staging Mach number and engine operation points constraints. The vehicle aerodynamic and weight data came from previous Beta II studies.

DISCUSSION AND RESULTS

For this study, three options were assessed as means to increase the overall performance of the Beta II vehicle: (1) Aerodynamic overspeeding of the TBE in the transonic (Mach 0.9 to 1.5) region in order to increase thrust and improve the booster's marginal thrust minus drag performance in that region; (2) Water injection during the transonic region at different turbine engine locations for the same purpose mentioned above; (3) Water injection at the turbine engine face to extend the top Mach number of the turbomachinery from Mach 2.4 up to 3.5. Uninstalled TBE performance using these options will be presented and discussed followed by the mission analysis. Uninstalled thrust was corrected for altitude effects along the flight trajectory using the engine face total pressure in atmospheres and is presented per propulsion module of 4 engines. Turbine engine specific fuel consumption (SFC) is based on total propellant used (fuel and water), not just the JP fuel.

OVERSPEED

Aerodynamic (and mechanical) overspeed of the TBE in the transonic was looked at in terms of performance. Generally turbine engine overspeeding is not used because it increases stress on the rotating components, increases the chance of compressor stall by operating in a region of reduced stall margin, and reduces engine life. However, overspeeding appears quite practical for short periods in vehicles with short duty cycles, such as the Beta II booster. In the transonic region, the vehicle has marginal thrust minus drag performance. Any increase in performance would improve acceleration during this period. For this reason, aerodynamic overspeeding of 7 and 10 percent were investigated to improve engine and vehicle performance.

Figure 4 shows that increasing the TBE rpm increases thrust, as expected. For the 7 percent overspeed thrust increases just over 5 percent, at 10 percent overspeed, the increase is just under 6 percent. This can be attributed to the increase in airflow, as seen in Figure 5. However, corrected airflow increases about 0.5 percent more than the thrust. The reason the thrust increase was slightly less than the increase in airflow is due to the slight decrease in compressor efficiency, which reduced the nozzle pressure ratio slightly. Since the TBE was run with the same maximum afterburning (same net exit fuel-to-air ratio) and the thrust increased almost directly with airflow, the SFC does not change significantly for the overspeed case compared to the baseline case, as shown in Figure 6.

TRANSONIC WATER INJECTION

Water injection was studied to determine its thrust enhancement potential in the transonic region to improve the booster's marginal thrust minus drag performance in this region. Water injection was done at the turbine engine face, in its main burner and the afterburner. Water addition at the engine face was limited by the vapor saturation limit. Additional water added beyond this limit would entail liquid water droplets impinging on the compressor blades, hurting its performance. However, significantly higher amounts of water could be added and evaporated in the main burner and afterburner.

Figures 7 and 8 shows the ratio of thrust with and without water injection versus percent water injected at different locations for the TBE at Mach 0.9 and Mach 1.5, the start and end of the transonic region. The percent water added is the ratio of water flow rate added, to the mass flow rate entering that component. Water injection at the engine face increases thrust the most for a given amount of water. This is caused by the cooling effect of the water, which reduces compressor entrance temperature. This also reduces its work and increases the airflow slightly. Water injection in the main burner allows more fuel to be added in that burner to maintain a constant exit temperature and some work will be derived from the heated water vapor passing through the turbine. However, with continuous maximum afterburning, the engine net exit fuel-to-air ratio is always at 0.95 of the stoichiometric value, meaning less fuel is added to the afterburner. The cooler nozzle entrance temperature reduces exhaust velocity, offsetting the increase in thrust from mass addition and slightly higher nozzle pressure ratio. Water injection in the afterburner initially increases thrust due to mass addition, but the effect is also offset by the reduction of nozzle exhaust velocity caused by the reduction of exhaust temperature. At 30 to 40 percent water injection, the increase in mass addition is insufficient to overcome the reduction in exhaust velocity and exit temperature and thrust actually decreases with increasing amounts of water. But before this point, engine SFC was above that of most rockets and probably would not even be considered for use.

To reduce the number of parameters, a constant ratio of 0.5 percent water was added throughout the transonic at the turbine engine face, or a constant 8.5 percent water added to the main burner or the afterburner. The percentage water added at the engine face was set by the minimum required to reach the saturation limit. For the main burner, 8.5 percent water injection was chosen for consistency with another turbine engine cycle run in companion studies (to be reported), was limited to this value. A similar value was chosen for the afterburner for comparison purposes between the main burner and afterburner cases. As can be seen in Figure 9, for the assumed amounts of water added, thrust increases most for the main burner, followed by the afterburner and the engine face, although it is always less than 4 percent.

Figure 10 shows that corrected airflow increases slightly when water is added at the turbine engine face, but does not have any effect for the other cases. This is because water injection at the turbine engine compressor face reduces the compressor entrance temperature, reducing its work. This changes the compressor/turbine matching with a net increase in turbine engine airflow capability. However, the thrust increase alone does not tell the whole story. Figure 11 shows that the increase in thrust can be very costly in terms of SFC. For the engine face, the amount of water injection was quite modest, as was the change in thrust and SFC. But for the case of water injection in the main burner, the SFC is extremely high. It is even worst for the afterburner. This is due to the fact that the percentage water added is based on the mass flow entering that component. For the main burner, it is the total TBE airflow minus the turbine bypass and turbine cooling flows, or about 70 percent of the total airflow. For the afterburner, the percentage is based on total TBE airflow (all bypass and cooling flows have been added back into the main flow path) plus main burner fuel, or about 103 percent of total airflow. This results in 50 percent more water added to the afterburner case relative to main burner case.

HIGH SPEED WATER INJECTION

The TBE had to spool down above Mach 2 to maintain the compressor exit temperature limit of 1810 °R. Without water injection, the TBE had to be shut down at Mach 3 because of the compressor exit temperature limit. For a HSCT engine, limited to Mach 2.4 entrance conditions, the turbomachinery would have to shut down before reaching Mach 3. Water injection at the turbine engine compressor face was investigated to maintain engine conditions similar to the design Mach number of 2.4, up to flight Mach numbers of 3.5. Water injection at the engine face seemed to be a viable alternative to using more expensive or exotic materials capable of the high temperatures, or shutting down the engine before desired.

As shown in Figure 12, modest amounts of water would be required to maintain Mach 2.4 engine entrance temperatures at speeds up to Mach 3.5. As seen in Figure 13, water injection past Mach 2.4 also helps keep the corrected airflow up. This has several positive effects on the engine, versus spooling down the engine, if further spooling down is possible. The water decreases entrance temperature, which reduces compressor work, and improves compressor corrected speed, mass flow, and compression capability. This also increases engine and nozzle pressure ratio, further increasing thrust, as seen in Figure 14. However, there is also a sharp increase in the SFC, especially at Mach 3.5, as shown by Figure 15.

MISSION ANALYSIS

A vehicle with constant aerodynamic properties and a take-off gross weight of 1 million pounds was used for the mission analysis (only the engine performance was changed for each case). The figure of merit was propellant used. Relative propellant used was determined by subtracting the baseline vehicle staging weight from the value for each case. The baseline staging weight is 853,700 pounds. Negative relative weights indicate a decrease in amount of propellant used, or a possible increase in payload capability.

As seen in Figure 16, overspeeding the TBE produces the greatest decrease in propellant used. This is due to the increase in thrust with no penalty in SFC. Water injection transonically always increases propellant usage, due to the small increase in thrust being overwhelmed by the much larger increase in SFC. Adding water at the engine face up to Mach 3 improves propellant usage because the thrust doubled for that point, while the SFC only increased by 50 percent. For Mach 3.25 and 3.5, SFC is increasing much faster than the thrust. But even with the large increase in SFC at Mach 3.5, the propellant usage increase is only about 5 percent.

The flight trajectories for cases using overspeeding are shown in Figure 17. As can be seen, differences in the flight path are very minor. Since the overspeed cases have slightly higher transonic thrust, they do not climb to as high an altitude or dive to as low an altitude as the baseline case to get through the marginal thrust minus drag transonic region. At the higher Mach numbers, the vehicle followed the dynamic pressure constraint to maximize thrust and minimize time.

The flight trajectories for cases using water injection in the transonic region are shown in Figure 18. For water injection at the main burner and afterburner, the vehicle climbs sooner, gaining some of the altitude for the dive through the transonic region before the engine starts using water injection. After that they also follow the dynamic pressure constraint.

Water injection at the turbine engine face to maintain Mach 2.4 engine entrance conditions up to Mach 3, 3.25, and 3.5, have some effect on the trajectory as seen in Figure 19. To reduce propellant usage, the mission code forces the vehicle to fly at reduced dynamic pressures (higher altitudes and lower levels of thrust and fuel flow).

SUMMARY

This study addressed the issue of improving the Beta II vehicle performance in the transonic region as well as extending the Mach number range of the turbomachinery. 3 methods of thrust enhancement were studied: (1) TBE overspeed in the transonic region; (2) Water injection at different locations in the TBE, also in the transonic region; (3) Water injection at the turbine engine face to extend its Mach number.

Overspeed in the transonic region showed modest (about 5 percent) gains in thrust. The thrust increase was essentially free, since the change in SFC was negligible. Water injection in the transonic region at different turbine engine locations did provide some increase in thrust. However, the thrust increase fell far short of the overspeed case and the cost of almost doubling SFC would hinder its use. Water injection at the turbine engine compressor face was able to extend TBE operation to Mach 3.5, with a considerable increase in thrust at the high Mach numbers, since the TBE did not have to spool down as much to maintain the compressor exit temperature constraint. The cost was high in terms of the SFC, it would be preferable to limit the extension to Mach 3 or 3.25, (about 1 Mach number), instead of Mach 3.5 to limit the increase in SFC. If the staging Mach number was reduced, water injection could extend the turbomachinery operating range sufficiently to reduce or eliminate ramjet propulsion requirements, simplifying the propulsion nacelle.

These engine performance options were judged in terms of propellant usage. Overspeed was the best option, but the improvement was less than 1 percent. Water injection from Mach 2.4 to 3.0, also gave a similar minimal improvement in staging weight. Water injection to extend the Mach range of the turbomachinery from Mach 2.4 to 3, 3.25 or 3.5 showed little increase in propellant usage (a negligible increase for extending the turbomachinery Mach number range up to 3.25 and only about 5 percent to extend it up to Mach 3.5). Transonic water injection at the engine face had little effect, but that was because the amount of water was so small. All other options increased propellant usage significantly, especially water injection in the afterburner, increasing propellant usage by over 30 percent.

Vehicle trajectory was fairly constant for most of the cases, except water injection in the main burner and afterburner. For these cases, the vehicle climbed subsonically, without water injection, to reduce the propellant used in the transonic (high SFC) region. In general, improved transonic thrust reduces the height of the climb and the depth of the dive through the transonic region. At higher Mach numbers, the trajectory followed the dynamic pressure limit to maintain the highest thrust levels, except when using water injection at the turbine engine face to extend the turbomachinery operating range, then a lower dynamic pressure path was chosen to minimize propellant.

This study indicates engine overspeeding is the best option to reduce propellant usage. Future work should seriously assess engine overspeeding to determine if undiscovered penalties would negate these results. Using water injection in the transonic region requires too much water for the increase in thrust for this particular vehicle and mission. However, water injection to extend the turbomachinery operating range increases thrust significantly, with only a slight increase in propellant usage. This suggests that further work should be performed to further assess its potential.

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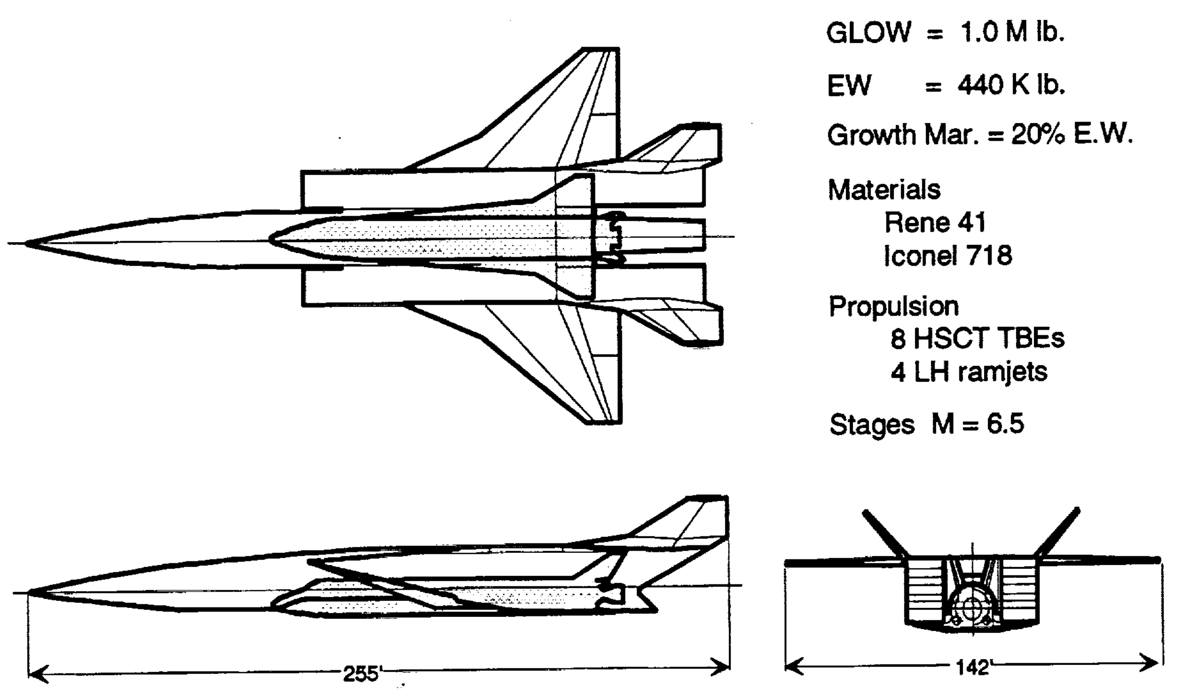

Figure 1. Beta II Configuration.

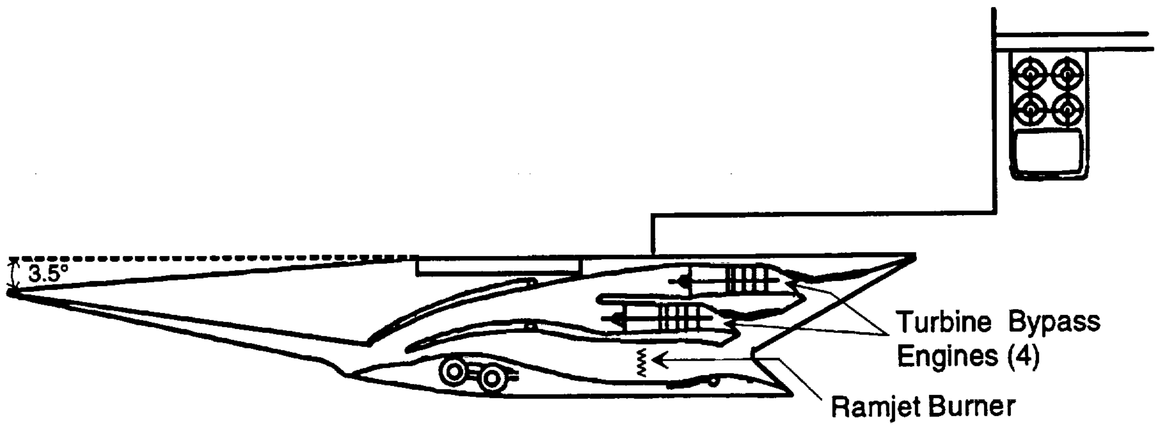

Figure 2. Beta II Nacelle Configuration.

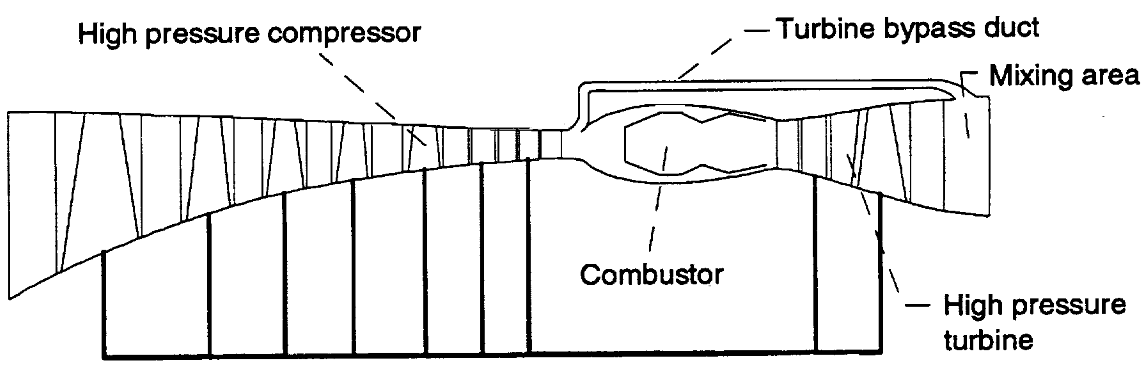

Figure 3. Turbine Bypass Engine Flowpath.

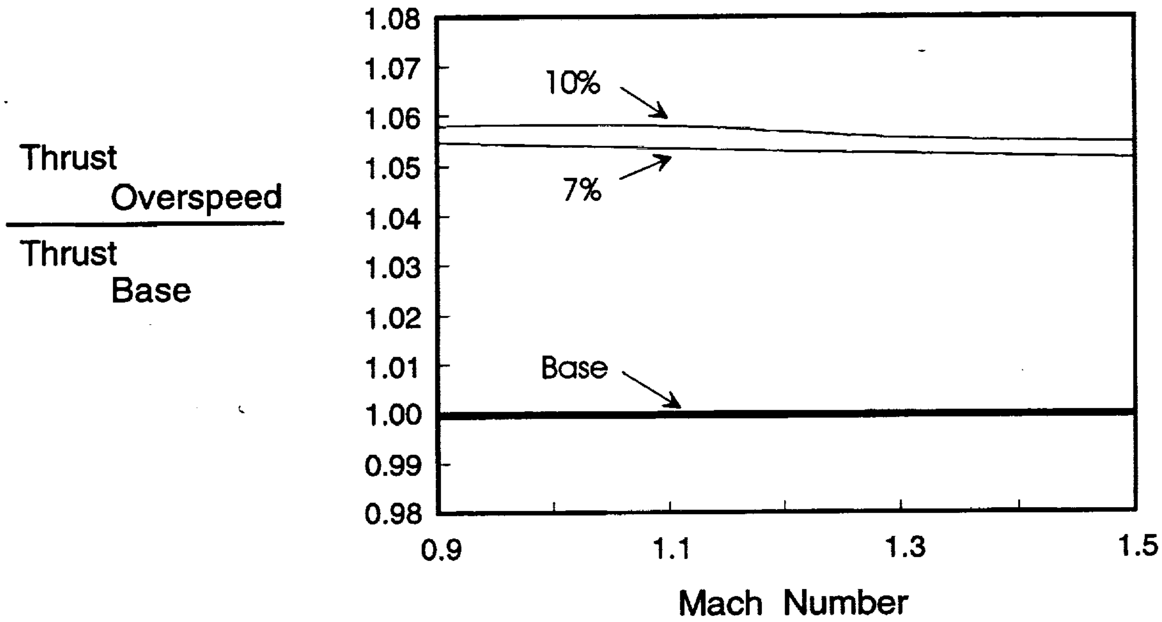

Figure 4. Effect of Transonic Overspeed on Thrust.

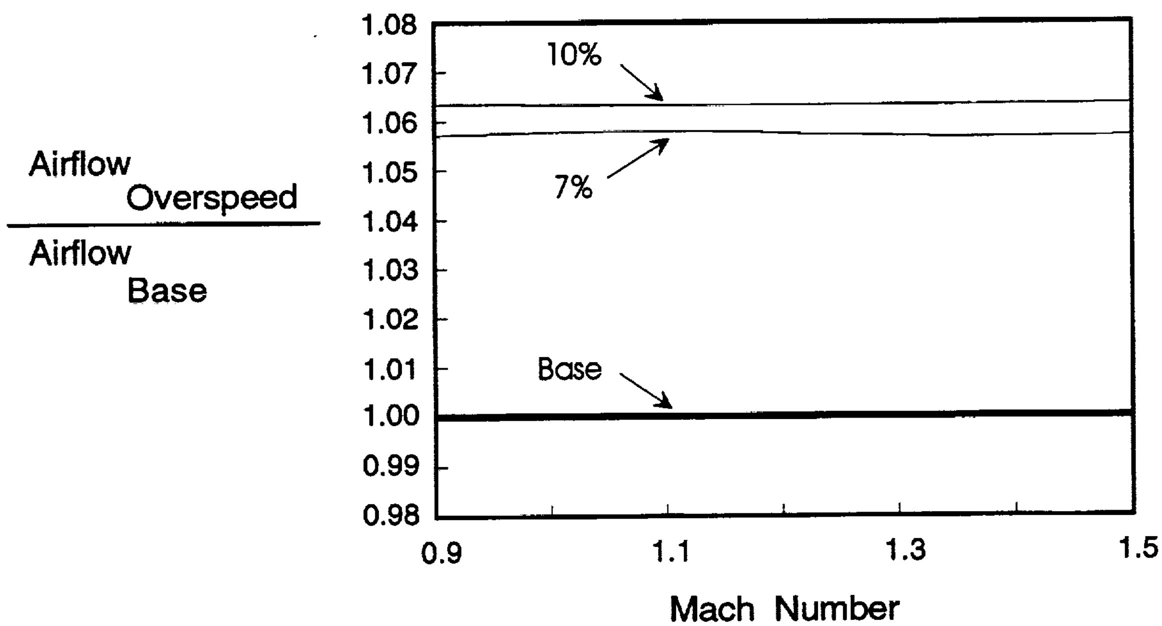

Figure 5. Effect of Transonic Overspeed on Airflow.

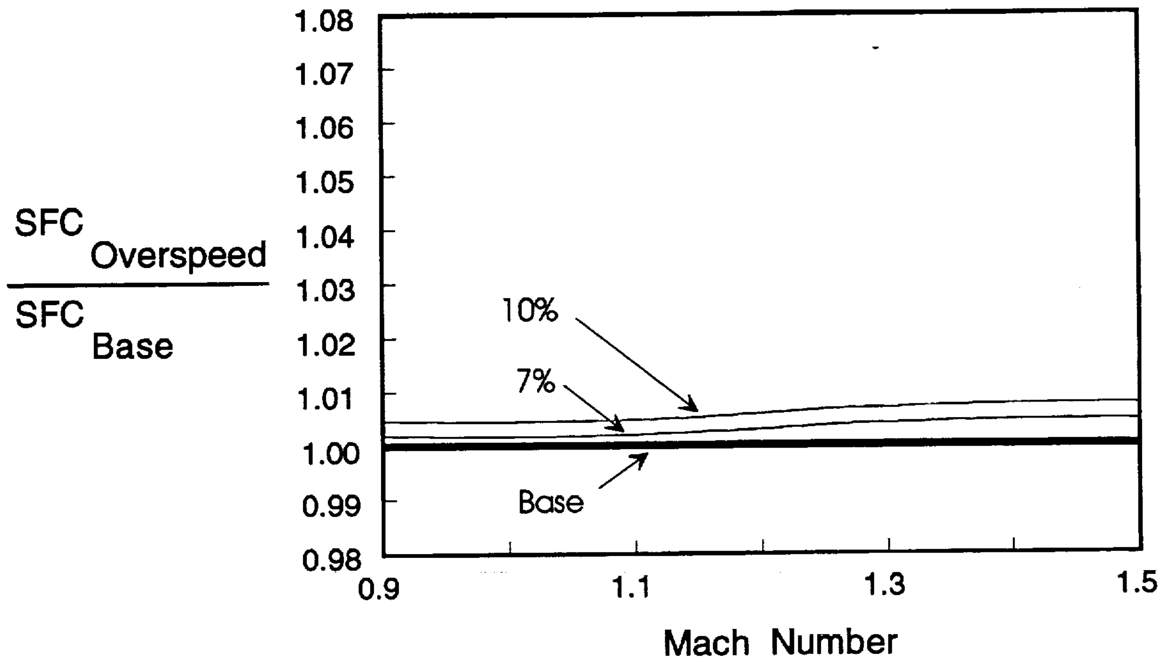

Figure 6. Effect of Transonic Overspeed on SFC.

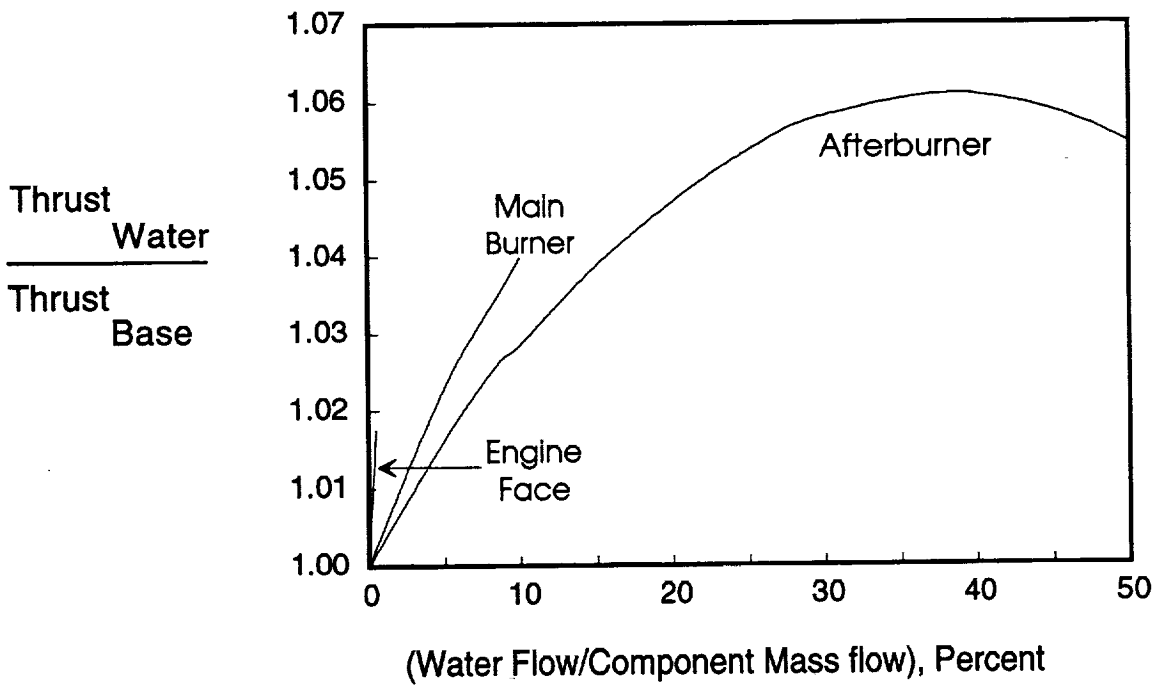

Figure 7. Effect of Water Injection at Mach 0.9.

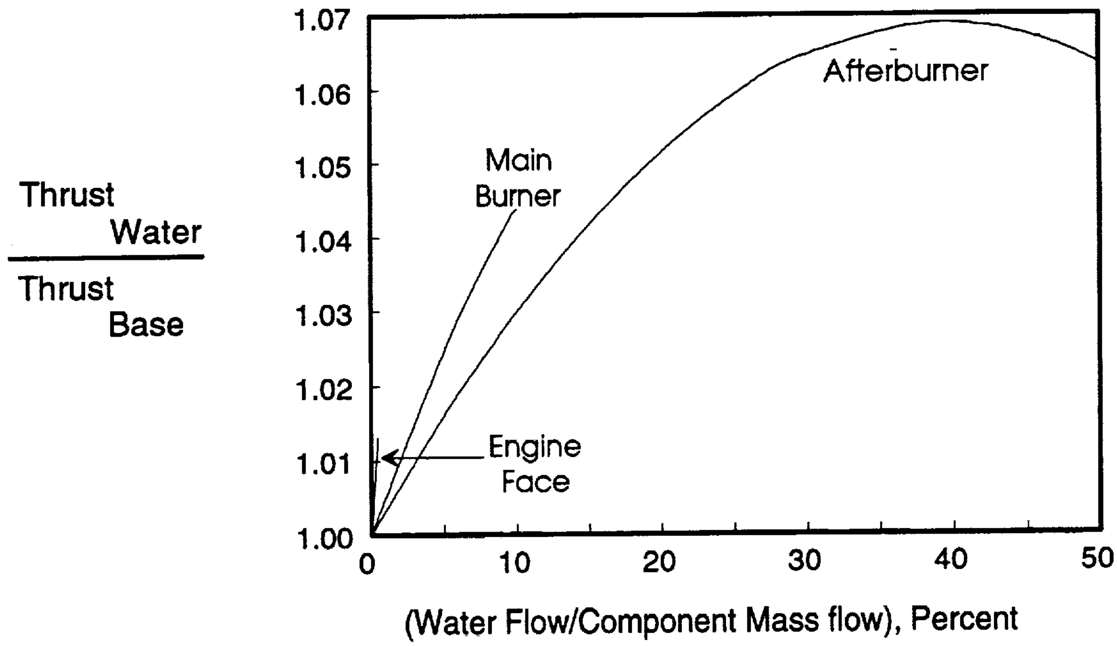

Figure 8. Effect of Water Injection at Mach 1.5.

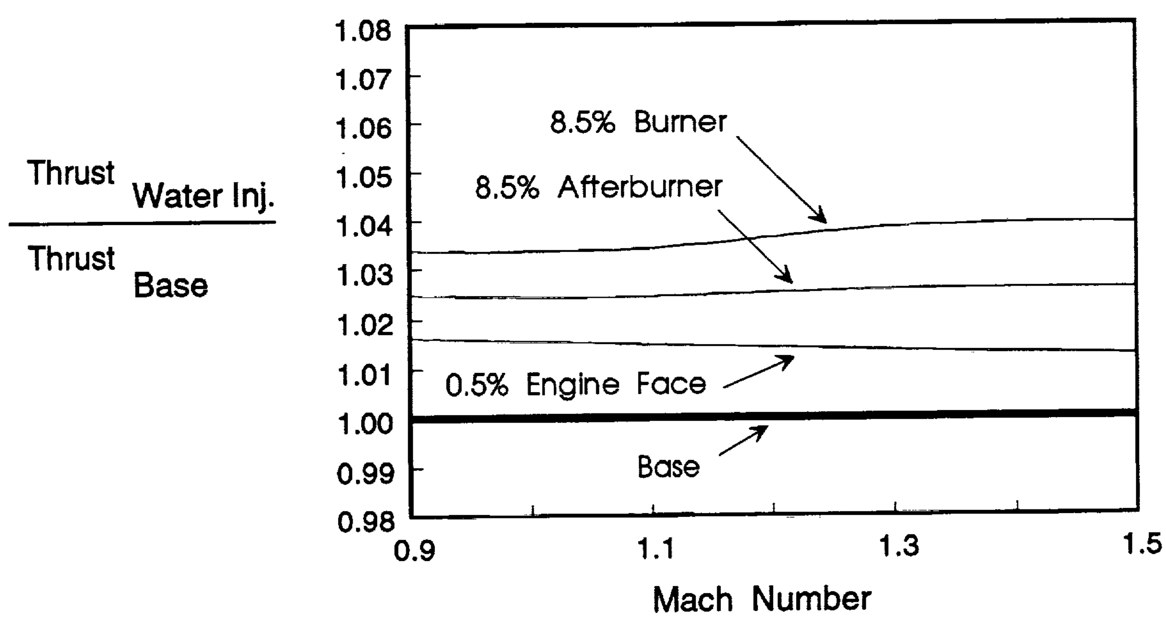

Figure 9. Effect of Transonic Water Injection on Thrust.

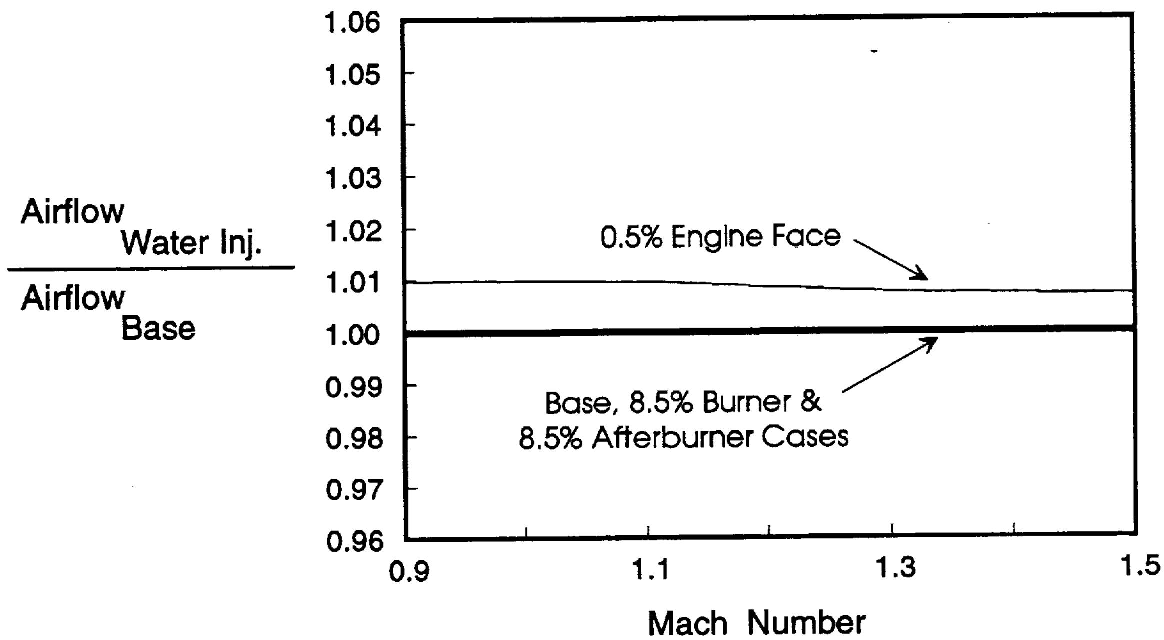

Figure 10. Effect of Transonic Water Injection on Airflow.

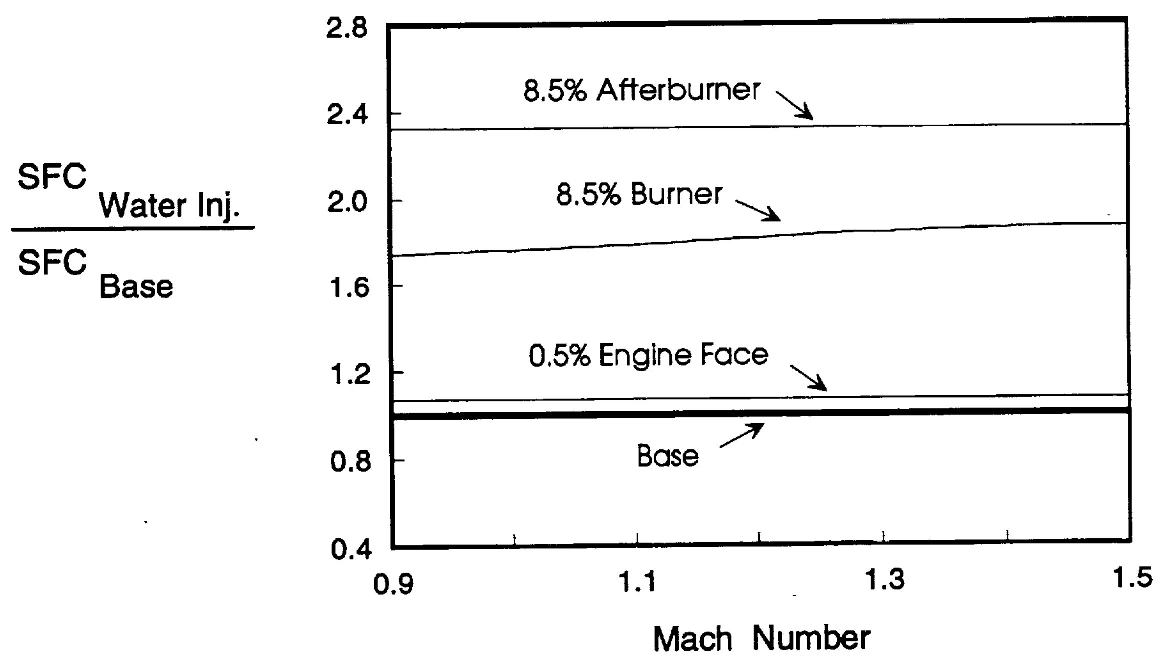

Figure 11. Effect of Transonic Water Injection on SFC.

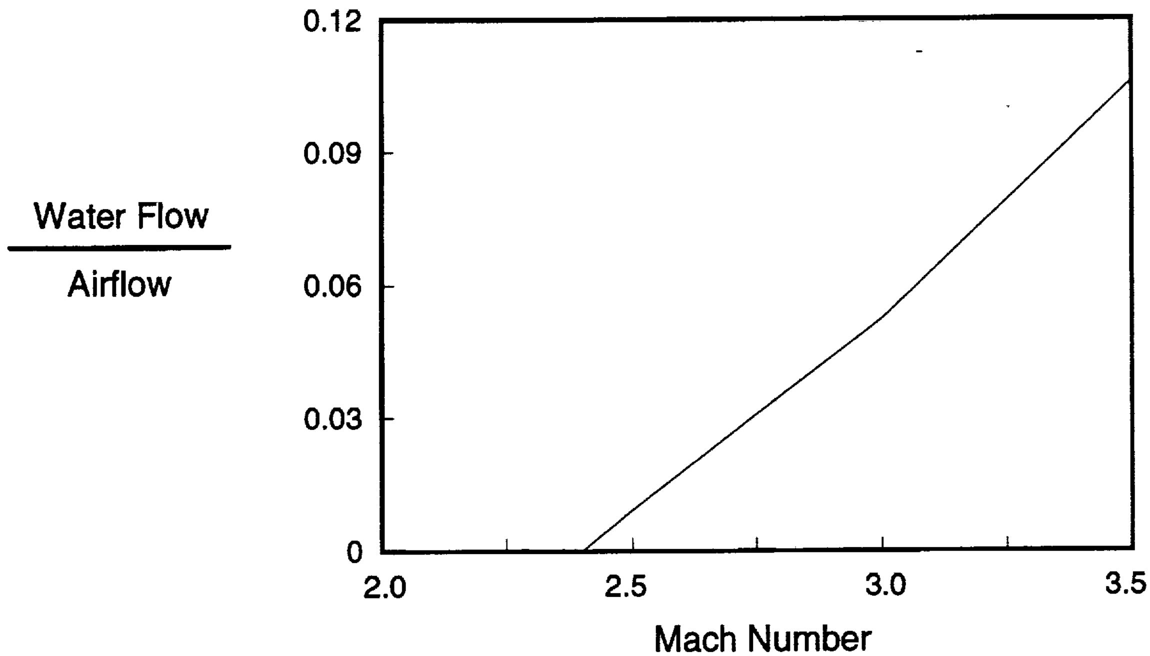

Figure 12. Amount of Water Required to Maintain Mach 2.4 Temperatures.

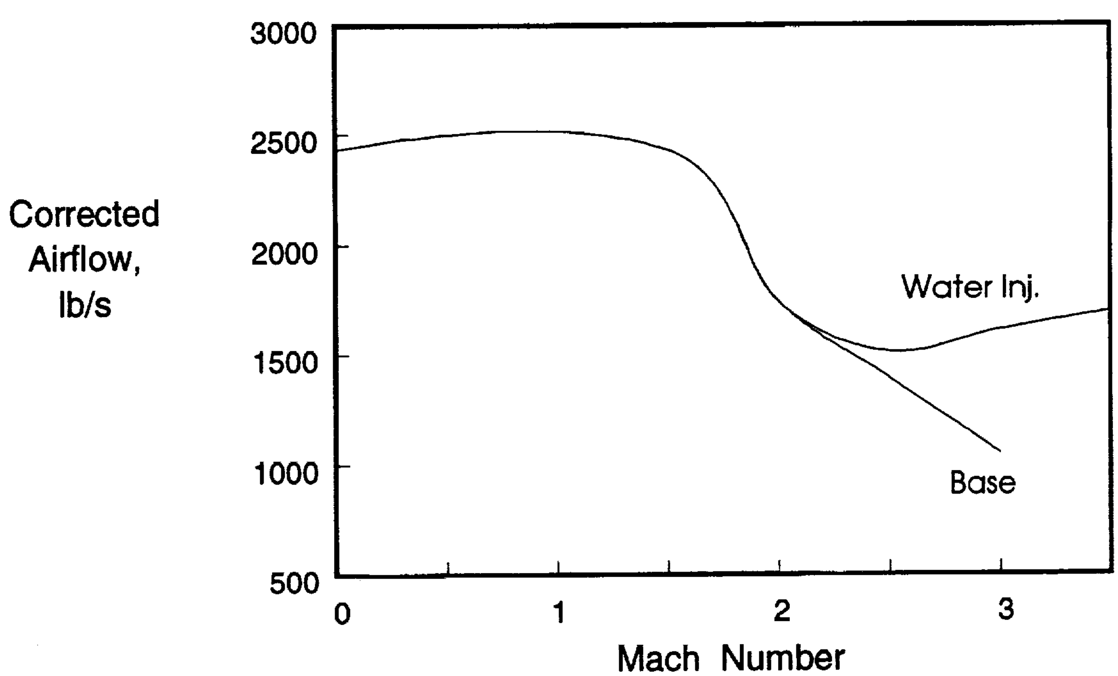

Figure 13. Effect of Water Injection at High Mach Numbers to Maintain Mach 2.4 Conditions on Airflow.

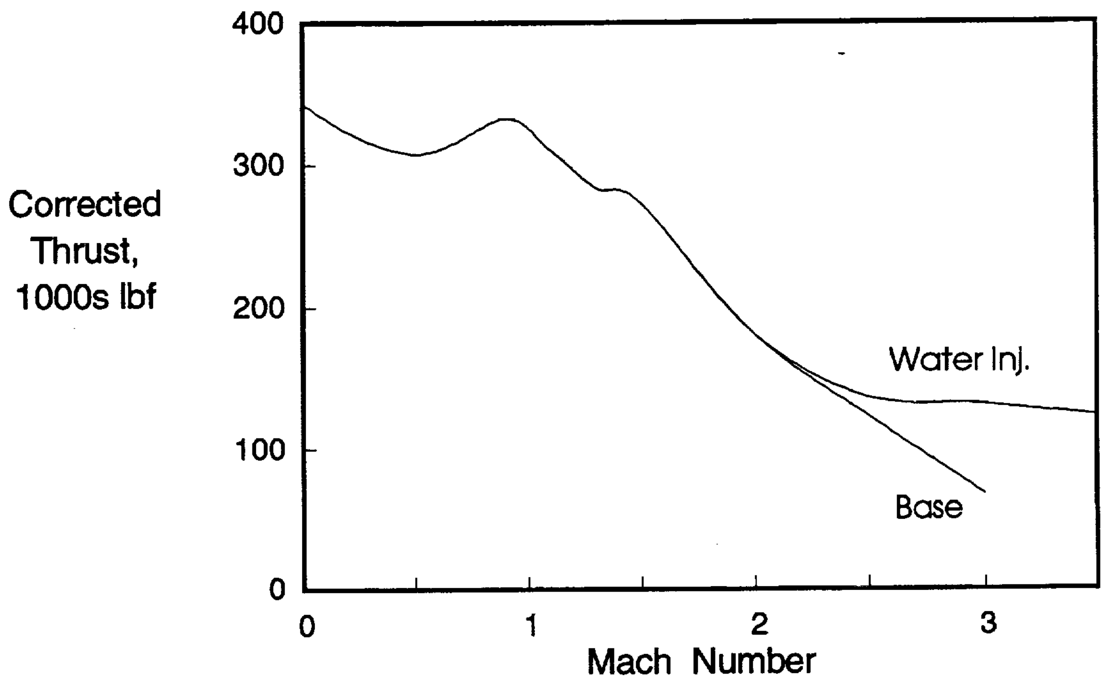

Figure 14. Effect of Water Injection at High Mach Numbers to Maintain Mach 2.4 Conditions on Thrust.

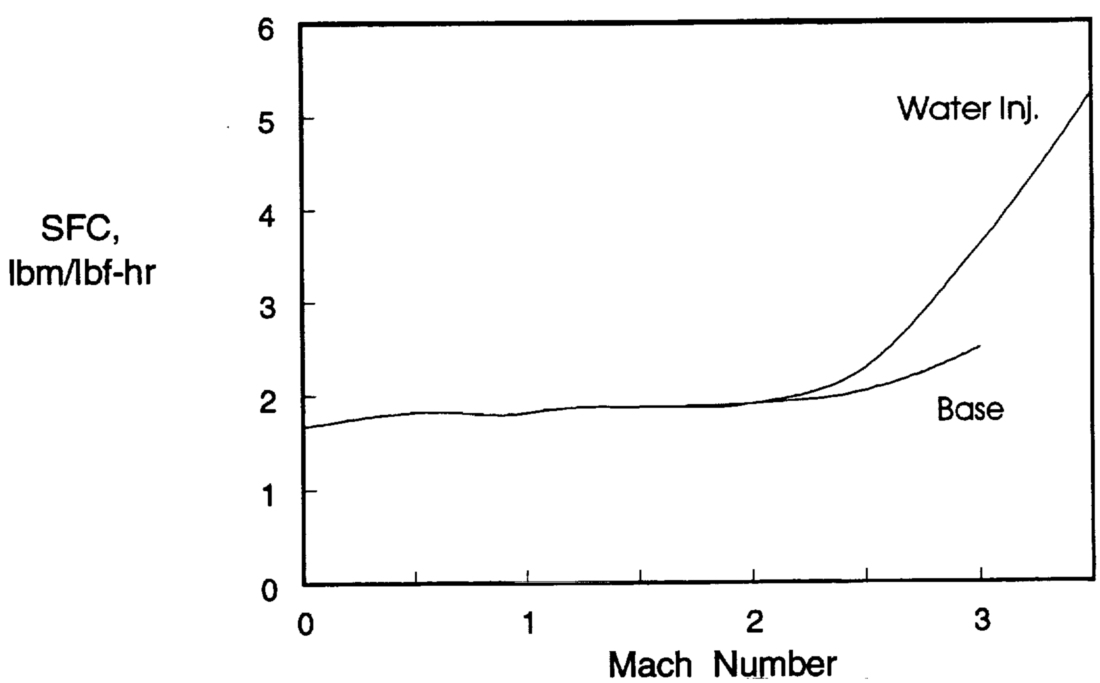

Figure 15. Effect of Water Injection at High Mach Numbres to Maintain Mach 2.4 Conditions on SFC.

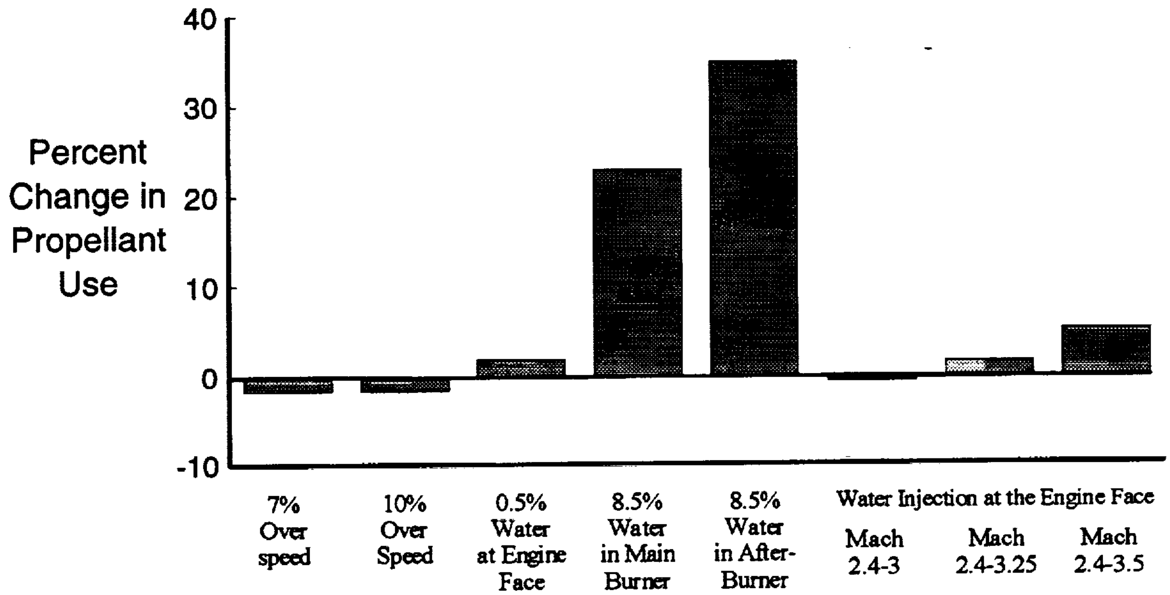

Figure 16. Vehicle Propellant Use Relative to the Baseline Case.

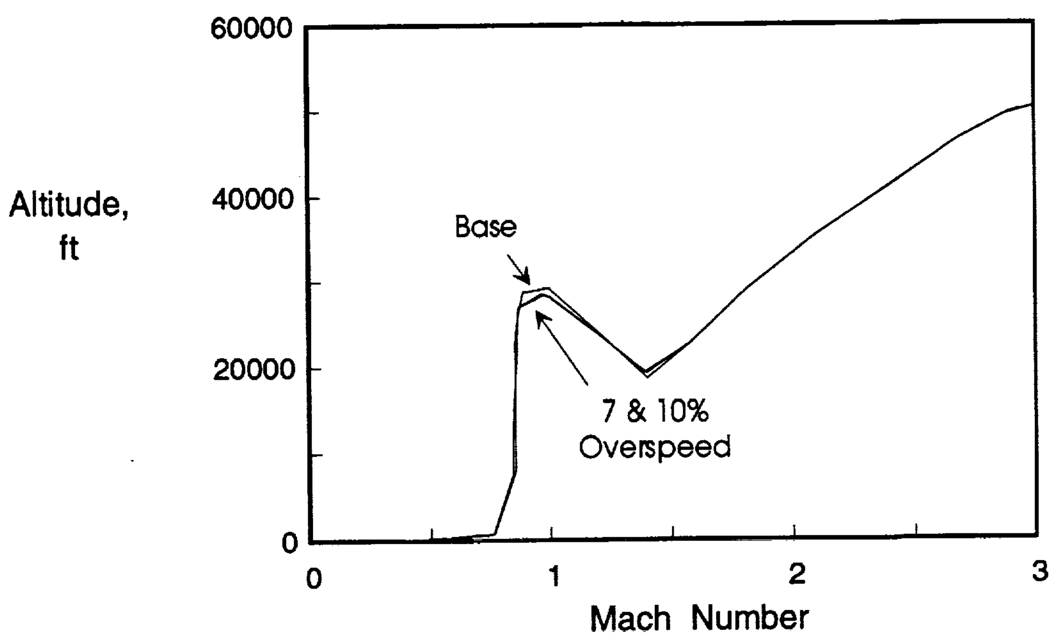

Figure 17. Flight Trajectory for Baseline and Overspeed Cases.

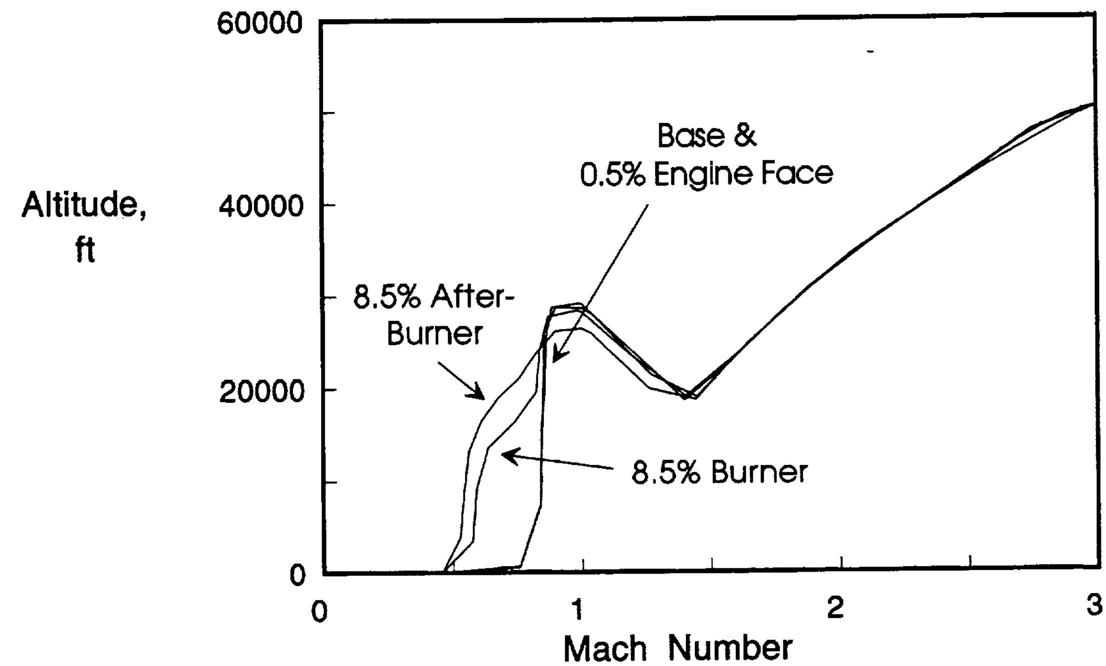

Figure 18. Flight Trajectory for the Baseline and Water Injection in the Transonic Region Cases.

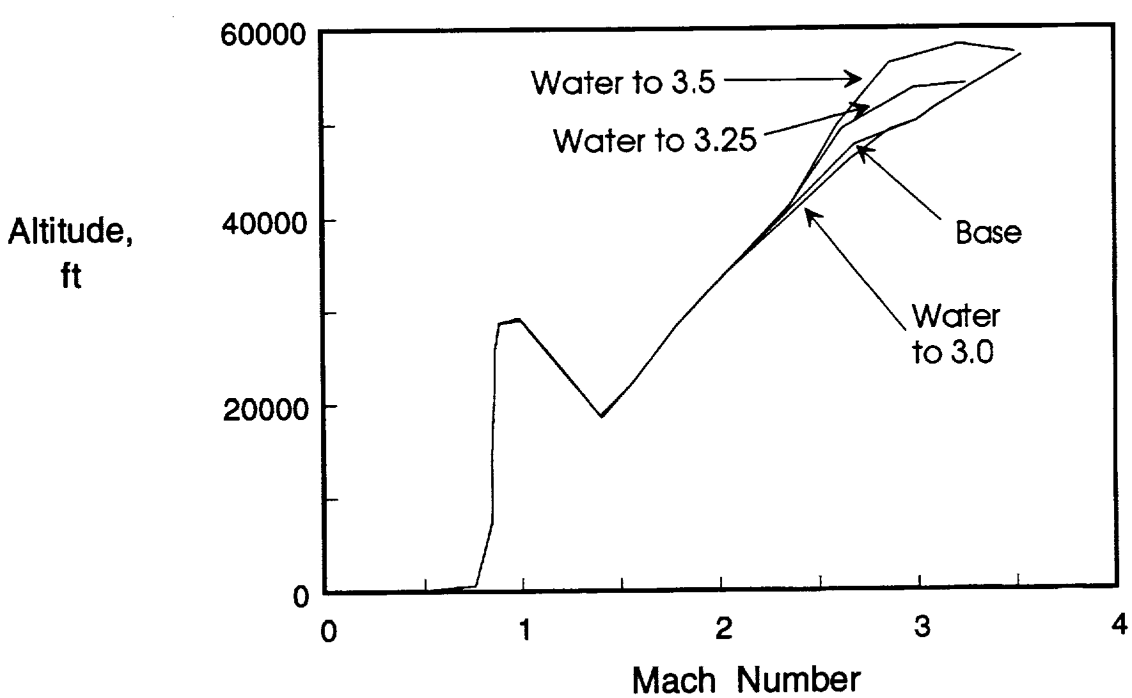

Figure 19. Flight Trajectory for the Baseline and Water Injections to Maintain Mach 2.4 Conditions at High Speed Cases.

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13. ABSTRACT ***(Maximum 200 words)***
NASA Lewis Research Center is continuing to study propulsion concepts for a horizontal takeoff and landing, fully reusable, two-stage-to-orbit vehicle. This will be capable of launching and returning a 10,000 pound payload to a 100 nautical mile polar orbit using low-risk technology. The vehicle, Beta II, is a derivative of the USAF/Boeing Beta vehicle which was designed to deliver a 50,000 pound payload to a similar orbit. Beta II stages at Mach 6.5 and about 100,000 feet altitude. The propulsion system for the booster is an over/under turbine bypass engine/ramjet configuration. In this paper, several options for thrust augmentation were studied in order to improve the performance of this engine where there was a critical need. Options studies were turbine engine overspeed in the transonic region, water injection at a various turbine engine locations also during the transonic region, and water injection at the turbine engine face during high speed operation. The methodology, constraints, propulsion performance and mission study results are presented.

14. SUBJECT TERMS
Air breathing engines; Transatmospheric vehicles; Gas turbine engines; Air breathing boosters; Aerospace planes

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